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ESTUARINE CIRCULATION PATTERNS

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ESTUARINE CIRCULATION PATTERNS[1]

D.W. Pritchard[2]

SYNOPSIS

Arguments are presented which indicate that there is a sequence of estuarine types, each with a distinct density stratification and circulation pattern. The position an estuary takes in this sequence depends primarily upon the river flow, tidal flow, width and depth.

The effect of each of these parameters upon the position an estuary takes in the estuarine sequence can be briefly stated as follows:

Other things being held equal, an estuary tends to shift from type A (highly stratified) through type B (moderately stratified) to type C or D (vertically homogeneous) with:

a) Decreasing river flow
b) Increasing tidal velocities
c) Increasing width
d) Decreasing depth

INTRODUCTION

For the purpose of this paper an estuary will be defined as a semi-enclosed coastal body of water having a free connection with the open sea and within which sea water is measurably diluted with fresh water run-off. We thus exclude from our discussion those embayments and lagoons which have been defined elsewhere (Pritchard,(1)) as neutral and inverse estuaries.

This paper treats the circulation in two groups of estuaries: (a) estuaries formed by the drowning of river mouths and the lower reaches of river valleys and (b) fiord type estuaries. The circulation in estuaries belonging to group (a) has been discussed by Stommel,(2) Stommel and Farmer,(3) Ketchum,(4,5) Pritchard,(6,7) Redfield,(8) and Rockford.(9) Fiord type estuaries have been discussed by Cameron,(10) Tulley,(11) and Redfield.(12) In this paper an integrated picture of estuarine circulation is presented. Many of the concepts presented here have been formulated by other authors, and no claim to complete originality is made. Specific references will, however, be kept to a minimum in the text.

Circulation and the Salt Balance in an Estuary

Within most estuaries the fresh water inflow exhibits a considerable seasonal fluctuation which is reflected in changes in the distribution of salinity

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2. Director, Chesapeake Bay Inst., The Johns Hopkins Univ., Annapolis, Md.

in the estuary. While these time changes in the salt content at any location are often quite significant in absolute magnitude, the relative magnitude of the net time change is in general small when compared to the several dominant, counter-balancing terms which contribute to the salt balance. The local time rate of change of salt content is equal to the sum of the effects of the advective processes and the nonadvective processes. The advective processes lead to a mass flux of water as well as a flux of salt, while the nonadvective processes are associated only with a flux of salt. The advective processes are associated with the net circulation pattern, and the nonadvective processes with the regime of turbulent or eddy mixing.

Let us assume that we have observed the salt content and the current velocities within a segment of an estuary over a period of one or more tidal cycles. The salt balance at a given point within this segment may be expressed by:

$$\frac{\partial s}{\partial t} = -v_1 \frac{\partial s}{\partial x_1} - v_2 \frac{\partial s}{\partial x_2} - v_3 \frac{\partial s}{\partial x_3} + \frac{\partial}{\partial x_1}\left\{K_1 \frac{\partial s}{\partial x_1}\right\} + \frac{\partial}{\partial x_2}\left\{K_2 \frac{\partial s}{\partial x_2}\right\} + \frac{\partial}{\partial x_3}\left\{K_3 \frac{\partial s}{\partial x_3}\right\} \tag{1}$$

Here x_1, x_2, and x_3 are the longitudinal, vertical and lateral coordinates respectively. The mean salt content averaged over one or more tidal cycles is represented by s, and the three components of the mean velocity are v_1, v_2, and v_3. The terms K_1, K_2, and K_3 are the eddy diffusivities in the three coordinate directions.

The first three terms on the right side of equation (1) are the advective terms, while the last three represent the nonadvective or turbulent diffusive processes. In general in any particular estuary we find that two or more of the terms on the right side of the equation dominate the salt balance. There exists an approximate dynamic equilibrium between several opposing processes, the result of which is a relatively slow net time change in the salt concentration. This does not mean that estuaries are always in steady state. However, in most cases, two or more of the terms on the right side of equation (1) are each an order of magnitude larger than the resulting net rate of change of salt concentration.

The character of the net circulation pattern within an estuary must exert a marked control on the salt balance, and must reflect the dominant processes which control this balance. It is therefore advantageous to discuss the circulation pattern in relationship to the processes which control the salt balance.

The Estuarine Sequence

An examination of various estuaries formed by the drowning of the lower reaches of river valleys shows a wide variation in the character of the circulation pattern, and hence in the processes which control the salt balance. There is evident a sequence of estuarine types ranging from the highly stratified salt-wedge estuary to the well mixed, vertically homogeneous estuary. It is not yet possible to state precisely the relationships between the various external physical factors and the circulation and mixing in an estuary. However, enough is now known so that the general character of estuarine circulation can be related to the more important physical phenomena such as river flow, tidal velocities, and the physical geography.

Coastal Plain Estuaries

To facilitate our understanding of actual estuarine circulation patterns let us first consider an idealized coastal plain estuary. This estuary is an elongated indenture in the coastline with a single river source of fresh water at the upper end and free connection with the sea at the lower end. First consider the situation in the absence of any tidal movements. In this case the fresh river water would flow out over the surface, and the sea water would protrude under the outflowing fresh water as a wedge. If there were no wind to promote mixing, and if the river flow were sufficiently low, there would be little exchange at the interface and the upper fresh water layer would flow out through the estuary with no increase in salt content. The salt wedge would be stationary and would extend to the fall line (the place where the river bottom rises above sea level). Because some mixing processes are always present no natural estuary represents this ideal situation.

As the rate of river inflow is increased interfacial waves will form between the fresh surface water and the underlying salt water wedge. At some critical relative speed these waves will become unstable and break, leading to an entrapment of some of the salt water from the wedge into the upper fresh water layer. In this situation there is little or no admixture of fresh water into the salt water wedge, but only the upward movement of salt water into the fresh water layer. The upper layer now increases its salt content as it moves seaward, and there must be a slow upstream movement of water in the salt water wedge to compensate for the loss upward into the fresh water.

The increased frictional drag that exists in this situation between the salt wedge and the upper, seaward flowing layer restricts the upstream protrusion of the wedge, so that it no longer can extend as far as the fall line. The greater the river flow the further downstream the upper edge of the wedge is found. Within the wedge increased upstream flow occurs to compensate for the increased loss of salt water upward into the fresher upper layer. Keulegan[13] has studied the salt wedge type estuary by utilizing flumes of various sizes, and has very nicely described the processes mentioned above.

While the breaking of the inter-facial wave into the upper layer has a superficial similarity to turbulent mixing, and hence the addition of salt to the upper layer might at first be thought of as a nonadvective flux, in actual fact the process brings about not only flux of salt but also a flux of mass from the salt wedge into the upper layer. Once the salt water is in the upper layer vertical mixing contributes to the spread of salt through the layer, but at the interface the primary process is vertical advection with the breaking of the interfacial waves producing a mean vertical velocity directed upward. If the wave breaking was associated with an entrapment of water from the upper layer into the lower layer as well, so that no net mass flux took place, then the process of salt flux upward would be a nonadvective one.

In such an estuarine system the two dominant terms in the salt balance would be the horizontal and vertical advections. That is, assuming quasi steady state, equation (1) would reduce approximately to

$$0 = -V_1 \frac{\partial s}{\partial x_1} - V_2 \frac{\partial s}{\partial x_2} \tag{2}$$

Within the upper layer, the vertical mixing term, $\frac{\partial}{\partial x_2}\left\{K_2 \frac{\partial s}{\partial x_2}\right\}$ would probably also be significant, but considering the gross salt flux, the vertical advection must be balanced by longitudinal advection.

The mouth of the Mississippi River is an excellent example of the salt wedge estuary described above. Such estuaries occur when (1) the ratio of river flow to tidal flow is relatively large, and (2) the ratio of width to depth is relatively small.

For purposes of convenient designation we will, in this discussion, designate the salt wedge estuary as type A. (See Fig. 1)

Now consider what happens to our ideal estuary when we introduce a tide of moderate amplitude. The tidal velocities, which must be nearly invariable with depth, will result in eddy motions as a consequence of both internal turbulence and boundary induced turbulence. Mixing now occurs between the lower layer of relatively high salt content and the upper layer of relatively low salt content. Not only does the salinity of the upper layer increase in the seaward direction, but the salt content of the lower layer now decreases toward the head of the estuary. Saltier water from the lower layer is also advected upwards into the upper layer.

In this type of estuary under steady state conditions there would be three important terms in equation (1). These are the horizontal advection, the vertical advection, and the vertical nonadvective term. Equation (1) becomes,

$$0 = -v_1 \frac{\partial s}{\partial x_1} - v_2 \frac{\partial s}{\partial x_2} + \frac{\partial}{\partial x_2}\left\{K_2 \frac{\partial s}{\partial x_2}\right\} \tag{3}$$

We will here designate estuaries exhibiting these features as type B estuaries. (See Fig. 2)

The net circulation pattern in type B estuaries involves flow volumes many times the volume of fresh water inflow. The net outflow in the upper layer may for example be as much as 40 times the river flow, with the compensating net upstream flow in the lower layer then being 39 times the river flow. Such a system is of considerable interest from an energy standpoint. A portion of the kinetic energy of the oscillatory streaming motion of the tide is converted into turbulence. The turbulence, by mixing the saltier under layer with the fresher upper layer, increases the potential energy of the mixture. This increased potential energy is then converted to kinetic energy of the net circulation. We thus here have an example of organized motion of one type feeding kinetic energy through a stage of disorganized motion into organized motion of a second type.

In the natural estuary the effect of the earth's rotation would result in a slight lateral salinity gradient. The boundary between the upper layer having a net downstream flow and the lower layer having a net upstream flow is not exactly horizontal, but slightly tilted. The upper layer extends to greater depths, and the net downstream flow is somewhat stronger, on the right hand side of the estuary than on the left, while the upstream flow occurs nearer the surface and is somewhat stronger on the left side of the estuary. The lateral terms in the salt balance equation associated with these lateral salinity and velocity gradients are of second order in a type B estuary.

The Chesapeake Bay and its tributary estuaries are good examples of this type of estuarine system. Velocity and salinity measurements obtained by the Corps of Engineers (14) indicate that the Savannah, Charleston, and Delaware estuaries are, at least partially, representatives of this estuarine type. The Savannah is, however, somewhat more highly stratified than the others mentioned, and hence may be considered intermediate between types A and B. On the other hand, the wider portions of Delaware Bay exhibit features characteristic of a third estuarine type, which will be discussed later.

Let us return to our idealized estuary and assume that the tidal velocities are further increased to the point where effective vertical homogeneity results. Now, though vertical turbulence is large, there can be no vertical flux of salt either through eddy diffusion or vertical advection since there is no vertical salinity gradient. There remains the longitudinal gradient, with increasing salt content in the seaward direction, and, as a result of the coriolis effect, a lateral gradient with higher salt content to the left of an observer facing the sea. The boundary between the lower salinity seaward flowing water and the higher salinity upstream flowing water, which in the case of the type B estuary is nearly horizontal, now becomes nearly vertical. The lower salinity downstream flowing water now occurs at all depths on the right hand side of the estuary, and the higher salinity upstream flowing water occurs at all depths on the left hand side of the estuary.

The vertical terms in equation (1) now disappear, and, under steady state conditions, we have

$$0 = -V_1 \frac{\partial s}{\partial x_1} - V_3 \frac{\partial s}{\partial x_3} + \frac{\partial}{\partial x_3}\left\{K_3 \frac{\partial s}{\partial x_3}\right\} \tag{4}$$

the dominant terms being the longitudinal advective term, the lateral advective term, and the lateral nonadvective or eddy diffusive term. Here, as in the case of the type A and B estuaries, the longitudinal nonadvective flux has been considered to be small compared to other terms in the equation. This matter will be discussed further below.

Estuaries having a circulation pattern and mixing regime similar to the one just described are here designated as type C estuaries. (See Fig. 3) There is evidence that the lower, relatively wide portions of the Delaware Bay and of the Raritan estuary are of this type.

Type C estuaries have relatively large tidal velocities and are relatively wide. In estuaries in which tidal mixing is sufficient to produce vertical homogeneity, but which are sufficiently narrow that the lateral mixing term destroys the lateral salinity gradient, no upstream advection develops on the left side of the estuary. These estuaries represent yet a fourth group which will here be designated as type D estuaries. (See Fig. 4)

In type D estuaries there is no upstream net advection. The upstream flux of salt necessary to balance the downstream advective flux due to river flow through the estuary must result from the longitudinal nonadvective flux. For this type of estuary equation (1) then becomes

$$0 = -V_1 \frac{\partial s}{\partial x_1} + \frac{\partial}{\partial x_1}\left\{K_1 \frac{\partial s}{\partial x_1}\right\} \tag{5}$$

Ketchum,[3] Arons and Stommel, [15] and later Stommel[16] have discussed flushing from this type of estuary. There is some tendency to consider that the flushing concepts applicable to this type of estuary are suitable approximations for evaluating the flushing from a majority of estuaries. It is my opinion that a relatively small number of estuaries actually fall within this group. It is unlikely that flushing concepts applicable to estuaries in which the salt balance is dominated by the longitudinal advective and nonadvective flux terms can be successfully used in the majority of natural estuaries.

It seems doubtful that the longitudinal nonadvective flux of salt upstream can successfully balance the downstream advective flux of salt unless the horizontal salinity gradient is appreciable. This would indicate that the length of type D estuaries would be relatively small, probably of the order of the length of several tidal excursions.

Fiord type Estuaries

The primary feature of a fiord is a deep elongated basin, having a U-shaped cross section, and a sill separating the basin from the sea whose depth compared to the depth of the main basin is relatively small. Many Norwegian fiords occur in complicated interconnecting systems in which the circulation pattern is probably quite complex. On the other hand, some of the fiords of the Canadian Pacific Coast more nearly fit our idealized description. Alberni Inlet, which has been studied by Tully[11] is essentially an elongated U-shaped trough with a basin depth of over 1000 feet and a sill depth at the outer threshhold of about 120 feet.

Typically, the source of fresh water inflow in a fiord type estuary, is a river entering the upper end of the fiord. The volume of water moved past any cross section by the tide is usually large compared to the volume introduced by the river, and the mixing is primarily related to the tidal velocities.

We will here confine our discussion to fiord type estuaries in which the controlling sill is over fifty feet in depth. The region of mixing between the fresh water and the sea water is apparently confined to a relatively thin layer of about 30 feet. Below this depth the basin is filled with water of the same salinity as found in the sea water at sill depth outside the fiord. Within the upper 30 feet a circulation pattern exists which is quite similar to that described for the type B coastal plain estuary. There occurs an upper seaward flowing layer in which the salt content increases in the seaward direction as a result of advection and mixing of saltier water from below. Between this upper seaward flowing layer and the relatively undiluted basin water an intermediate layer occurs in which the net flow is directed up the estuary. The large volume of basin water with salinities characteristic of the sea water outside the fiord exhibits very slow movements. Tulley[11] reports that the boundary between the upper layer and the intermediate layer occurs at a depth of about 10 feet, and that relatively undiluted ocean water is found below a depth of 30 feet.

While the circulation and mixing in the upper 30 feet or so of the fiord type estuary appear to be similar to that described for the type B coastal plain estuary, the vertical salinity structure is quite different. In the fully developed type B estuary the longitudinal salinity gradient is approximately constant with depth. The shape of the vertical salinity curve does not vary greatly with position in the type B estuary, and the difference in mean salinity of the upper layer and the lower layer remains nearly the same along the length of the estuary. In a fiord type estuary high salinity water occurs throughout the estuary in the deep zone, and the vertical salinity structure varies markedly along the length of the estuary, approaching more nearly the characteristics of a type A coastal plain estuary when this feature is considered.

The upstream motion is primarily confined to the relatively thin intermediate layer, with little perceptible net movement occuring in the deep zone.

The fiord type estuary might be considered as a type B estuary in which the bottom has been replaced by a basin of undiluted sea water.

Some General Relationships Between Certain Physical Parameters and the Estuarine Sequence

The important physical parameters which control the sequence of estuarine types are the river flow, the tide, the mean depth of the estuary and the width of the estuary. Let us briefly evaluate the effect of these parameters.

In this evaluation we will consider an elongated indenture in the coast line with a river flowing into the upper end. We will consider variations in width, depth, river flow and tidal velocity.

It is recognized that for a given set of tidal characteristics of the ocean just outside the estuary, the tidal velocities in the estuary will depend upon the width, depth, and length of the estuary. Since it is not the purpose of this paper to go into the complexities of these inter-relationships involving tidal hydraulics, I have chosen to consider the tidal velocity as the primary parameter rather than the tidal characteristics of the ocean at the mouth of the estuary.

Let us suppose that the width, depth, and tidal velocities remain the same in our ideal estuary, and that we investigate the effect of different steady state river flows. When the river flow is such that the volume inflow during a tidal cycle is large compared to the tidal flow, the estuary will have the characteristics of a type A estuary. If the flow is decreased to a point where the tidal flows are large compared to the river flow per tidal cycle, then the estuary will exhibit the characteristics of a type B estuary. For example, the Savannah River shows conditions similar to a salt wedge estuary (type A) for river flows of 60,000 to 70,000 sec ft., and yet for flows of 5,000 to 10,000 sec ft. this estuary shows type B characteristics.

As the flow becomes still smaller the tidal velocities can more effectively overcome the vertical stability and our ideal estuary shows the characteristics of either a type C or a type D estuary.

Now suppose that the width, depth and river flow remained the same and consider the effect of different tidal velocities. If there were no tide the estuary would be type A. As the tidal velocity increased the estuary would show characteristics of type B, and finally of either type C or type D at very high tidal velocities.

If the river flow and tidal velocities are kept constant, and the cross sectional area of our ideal estuary is varied by changing the width of the estuary, then we are in effect changing the ratio of tidal volume to river flow, since the same tidal velocities will pass a greater volume of water through a large cross section than through a small one. Since it is the volume of water per unit time which is considered in the river flow, a larger cross section implies lower net velocities related to river flow alone. The net result of increasing the width of the estuary is then the same as that obtained by decreasing the river flow. The estuarine sequence would tend to shift from type A towards type C for increasing width.

The effect of varying the depth, while holding the other parameters constant, is quite different from the effect of varying the width. An increase in depth does increase the cross sectional area and hence apparently decreases the ratio of river flow to tidal flow. However, the increase in depth also results in lowering the effectiveness of the tidal velocities in promoting vertical mixing, and the system tends to become more highly stratified. The river outflow is therefore more effectively confined to the upper layer. The effect of increasing the depth would then in general have an effect opposite to that of increasing the width, and would correspond to decreasing the tidal velocities. The estuary sequence would tend to shift from type C towards type A for increasing depth.

Whether a vertically homogeneous estuary will be of type C or of type D is primarily controlled by the width of the estuary. Relatively wide estuaries in which the tidal mixing is sufficient to produce vertical homogeneity will show the characteristics of type C, while relatively narrow ones will be more like a type D estuary.

SUMMARY

The drowned river valley coastal plain estuaries characteristic of the Atlantic and Gulf coasts can be classified in a sequence of estuarine types.

The circulation pattern in the type A estuary is dominated by the river flow. A salt water wedge extends under the seaward flowing upper layer; the greater the river flow the further downstream the edge of this wedge occurs. Salt water is advected into the upper layer from the wedge, but there is little or no mixing of fresh water down into the wedge. The volume of flow in the upper layer increases in the seaward direction as salt water is added from below. A return flow must occur in the wedge to compensate for this loss of water from the wedge. This return flow is generally small compared to the river flow. Tidal mixing is relatively unimportant in this type of estuary. (See Figure 1)

Tidal mixing plays an important role in the circulation of the type B estuary. Here mixing occurs between the upper, seaward-flowing layer and the higher salinity water flowing up the estuary along the bottom. The volumes of flow involved in this net circulation pattern are often many times the volume of fresh water inflow. Thus at the mouth of the James River about 20 times the volume of the river discharge flows out of the estuary in the upper layer, and a compensating flow of 19 times the river discharge flows up the estuary in the lower layer. (See Figure 2)

In the type C estuary the vertical mixing is so intense that the estuary becomes vertically homogeneous. The salt balance can no longer be maintained by a vertically stratified flow system, and instead a lateral flow pattern exists. The lower salinity outflow occurs along the right side of the estuary, and the return compensating flow of higher salinity water is found along the left side of the estuary. Lateral advection and lateral eddy mixing of salt take place in this type estuary in order to maintain the salt balance. (See Figure 3)

In vertically homogeneous estuaries in which the lateral mixing is sufficient to destroy the lateral salinity gradient, the salt balance must be maintained by a balance between the longitudinal flux of salt out of the estuary by advection and the longitudinal flux of salt into the estuary by longitudinal mixing. Such estuaries cannot be much longer than the length defined by several tidal excursions. This type estuary has been classified as type D. (See Figure 4)

In conclusion, other things being held equal, an estuary tends to shift from type A through type B to type C (or D) with:

a) Decreasing river flow
b) Increasing tidal velocities
c) Increasing width
d) Decreasing depth

It is recognized that other external factors, such as wind velocity, air temperature, solar radiation, and bottom roughness, will play a part in controlling the vertical stratification and hence the circulation characteristics. It is believed that these are generally less important than the four parameters discussed here.

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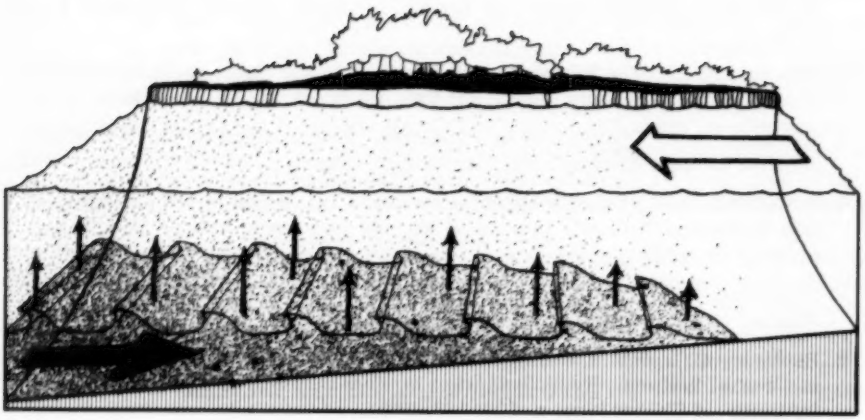

Figure 1

Type A Estuary

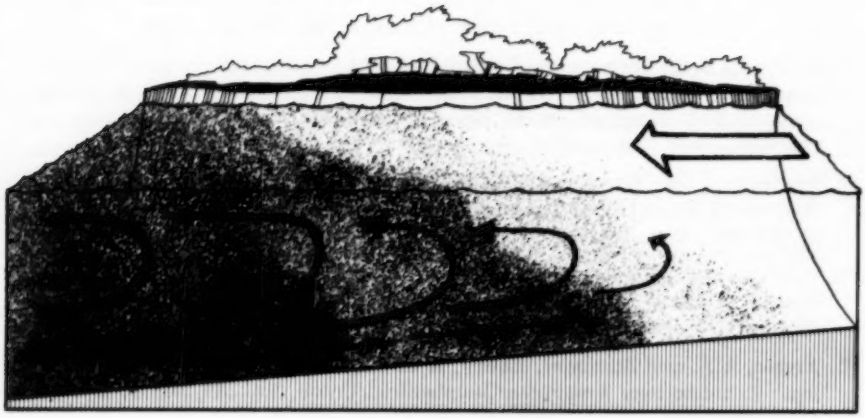

Figure 2

Type B Estuary

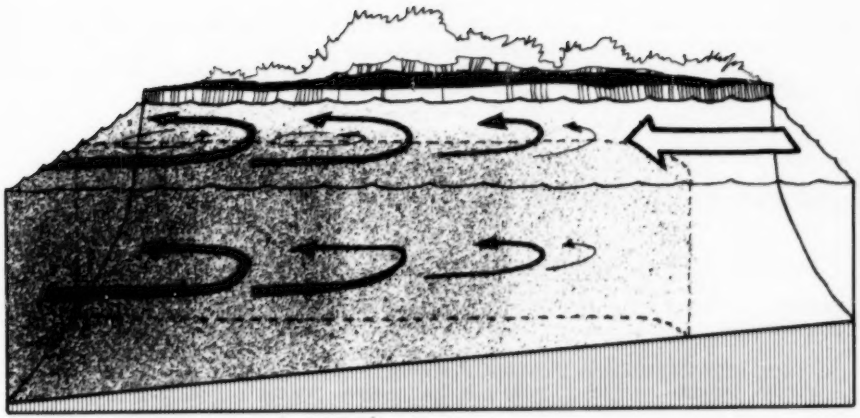

Figure 3

Type C Estuary

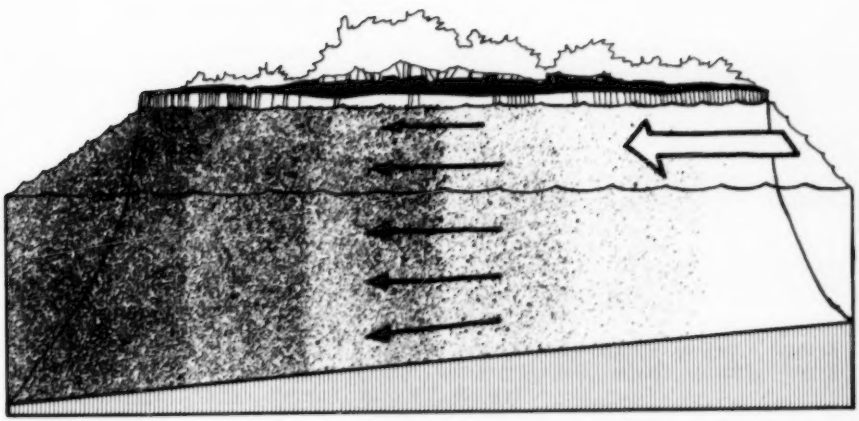

Figure 4

Type D Estuary

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VOLUME 80 (1954)

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JULY: 457(AT), 458(AT), 459(AT)[c], 460(IR), 461(IR), 462(IR), 463(IR)[c], 464(PO), 465(PO)[c].

AUGUST: 466(HY), 467(HY), 468(ST), 469(ST), 470(ST), 471(SA), 472(SA), 473(SA), 474(SA), 475(SM), 476(SM), 477(SM), 478(SM)[c], 479(HY)[c], 480(ST)[c], 481(SA)[c], 482(HY), 483(HY).

SEPTEMBER: 484(ST), 485(ST), 486(ST), 487(CP)[c], 488(ST)[c], 489(HY), 490(HY), 491(HY)[c], 492(SA), 493(SA), 494(SA), 495(SA), 496(SA), 497(SA), 498(SA), 499(HW), 500(HW), 501(HW)[c], 502(WW), 503(WW), 504(WW)[c], 505(CO), 506(CO)[c], 507(CP), 508(CP), 509(CP), 510(CP), 511(CP).

OCTOBER: 512(SM), 513(SM), 514(SM), 515(SM), 516(SM), 517(PO), 518(SM)[c], 519(IR), 520(IR), 521(IR), 522(IR)[c], 523(AT)[c], 524(SU), 525(SU)[c], 526(EM), 527(EM), 528(EM), 529(EM), 530(EM)[c], 531(EM), 532(EM)[c], 533(PO).

NOVEMBER: 534(HY), 535(HY), 536(HY), 537(HY), 538(HY)[c], 539(ST), 540(ST), 541(ST), 542(ST), 543(ST), 544(ST), 545(SA), 546(SA), 547(SA), 548(SM), 549(SM), 550(SM), 551(SM), 552(SA), 553(SM)[c], 554(SA), 555(SA), 556(SA), 557(SA).

DECEMBER: 558(ST), 559(ST), 560(ST), 561(ST), 562(ST), 563(ST)[c], 564(HY), 565(HY), 566(HY), 567(HY), 568(HY)[c], 569(SM), 570(SM), 571(SM), 572(SM)[c], 573(SM)[c], 574(SU), 575(SU), 576(SU), 577(SU), 578(HY), 579(ST), 580(SU), 581(SU), 582(Index).

VOLUME 81 (1955)

JANUARY: 583(ST), 584(ST), 585(ST), 586(ST), 587(ST), 588(ST), 589(ST)[c], 590(SA), 591(SA), 592(SA), 593(SA), 594(SA), 595(SA)[c], 596(HW), 597(HW), 598(HW)[c], 599(CP), 600(CP), 601(CP), 602(CP), 603(CP), 604(EM), 605(EM), 606(EM)[c], 607(EM).

FEBRUARY: 608(WW), 609(WW), 610(WW), 611(WW), 612(WW), 613(WW), 614(WW), 615(WW), 616(WW), 617(IR), 618(IR), 619(IR), 620(IR), 621(IR)[c], 622(IR), 623(IR), 624(HY)[c], 625(HY), 626(HY), 627(HY), 628(HY), 629(HY), 630(HY), 631(HY), 632(CO), 633(CO).

MARCH: 634(PO), 635(PO), 636(PO), 637(PO), 638(PO), 639(PO), 640(PO), 641(PO)[c], 642(SA), 643(SA), 644(SA), 645(SA), 646(SA), 647(SA)[c], 648(ST), 649(ST), 650(ST), 651(ST), 652(ST), 653(ST), 654(ST)[c], 655(SA), 656(SM)[c], 657(SM)[c], 658(SM)[c].

APRIL: 659(ST), 660(ST), 661(ST)[c], 662(ST), 663(ST), 664(ST)[c], 665(HY)[c], 666(HY), 667(HY), 668(HY), 669(HY), 670(EM), 671(EM), 672(EM), 673(EM), 674(EM), 675(EM), 676(EM), 677(EM), 678(HY).

MAY: 679(ST), 680(ST), 681(ST), 682(ST)[c], 683(ST), 684(ST), 685(SA), 686(SA), 687(SA), 688(SA), 689(SA)[c], 690(EM), 691(EM), 692(EM), 693(EM), 694(EM), 695(EM), 696(PO), 697(PO), 698(SA), 699(PO)[c], 700(PO), 701(ST)[c].

JUNE: 702(HW), 703(HW), 704(HW)[c], 705(IR), 706(IR), 707(IR), 708(IR), 709(HY)[c], 710(CP), 711(CP), 712(CP), 713(CP)[c], 714(HY), 715(HY), 716(HY), 717(HY), 718(SM)[c], 719(HY)[c], 720(AT), 721(AT), 722(SU), 723(WW), 724(WW), 725(WW), 726(WW)[c], 727(WW), 728(IR), 729(IR), 730(SU)[c], 731(SU).

c. Discussion of several papers, grouped by Divisions.

e. Presented at the Atlantic City (N.J.) Convention in June, 1954.

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